Research Progress and Prospects of Microplastics Treatment in Wastewater

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Abstract: With the wide application of plastics, it leads to a large amount of plastic waste. In particular, microplastics, which are difficult to degrade, have become an important pollution problem in the global ecological environment. This paper provides a detailed review of the classification and characteristics of microplastics and their environmental and health impacts, and a systematic summary of existing microplastic treatment methods, including physical, chemical and biological methods. This paper concludes that microplastics are widespread in water bodies and have far-reaching impacts on the environment, including soil and groundwater. Among them, the issue of the potential toxicity of microplastics to living organisms (including humans) has also attracted widespread attention. In addition, this paper analyses the effectiveness of different treatment processes and the challenges they face, using the treatment of microplastics in wastewater treatment plants as an example. It is shown that the existing treatment technologies, although effective in reducing the discharge of microplastics, still have certain limitations, such as the problem of secondary contamination of microplastics. For this reason, future research should focus on more efficient and sustainable microplastic degradation technologies to better address this global environmental challenge.

1 INTRODUCTION

Plastics are synthetic polymers extracted from organic products such as coal, natural gas, salt, cellulose and crude oil (Kasmuri, 2022), which are widely used in food, textile, construction, industry, medical and other production and life due to their lightweight, stable nature, low cost, and long-lasting durability. However, with time, a large number of plastics become solid waste, entering the corners of the city to affect human life, and even entering the ecological environment to hinder balanced development.

Studies have shown that the degradation cycle of plastic waste is so long that it can be considered almost non-degradable. Given that the degradation of plastics occurs through photodegradation rather than biodegradation, it implies that plastics can only undergo a gradual decomposition from a substantial mass into microplastics with a reduced particle size (< 5 mm) under environmental conditions (Geng, 2024). Microplastics are highly adsorbent and resistant to biodegradation, accumulating in the environment and, due to their small size and widespread presence in the ecosystem, causing many adverse effects, and have become one of the most serious emerging environmental problems. If microplastics are prevalent in the marine environment, they could pose a significant threat to biota. Their composition and relatively large surface area render them prone to the adsorption of aqueous organic pollutants and the leaching of toxic plasticizers (Cole, 2011). Additionally, microplastics can adsorb hydrophobic organic pollutants from the water, leading to complex contamination issues and potential toxicity-enrichment problems within ecosystems. Therefore, the treatment of microplastics is urgent.

At present, the treatment of microplastics exists in the physical, chemical, biological, and other traditional methods, as well as the more emerging advanced oxidation and catalyst methods. For microplastics in the water body, the current main need

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to rely on the treatment process of sewage plant, through the screen grid composed of primary treatment and secondary biological treatment, can remove microplastics with a particle size greater than 500 microns (Park, 2021), after the tertiary treatment, most of the use of coagulation settling tanks to make the microplastics settle, but also studies have shown that the use of membrane technology (such as nano-filtration membranes) to achieve a better removal effect (Sharma, 2022). In practice, wastewater plants also introduce air flotation tanks, biological treatment, advanced oxidation and other methods for deeply treating microplastics in wastewater. However, this method also has certain defects, that is, the microplastics removed by sedimentation will accumulate in the sludge, along with the solid waste excluded from the sewage plant, if not properly handled will produce secondary pollution.

In conclusion, microplastics are an environmental problem caused by human production and life, which spreads widely until it threatens our lives. Compared with the situation of microplastic pollution, the treatment of microplastics in wastewater still lacks a clear generalized system, and microplastics discharged with sludge have not been given due attention. The purpose of this paper is to study the current treatment methods of microplastics, firstly, to introduce the classification and characteristics of microplastics, secondly, to summarize the existing physical, chemical and biological methods for the treatment of microplastics, and finally, to take microplastics treatment in wastewater treatment as an example of the systematic application and analysis of the above methods.

2 OVERVIEW OF MICROPLASTICS

The more common microplastics can be divided into two main categories. Plastics manufactured to microscopic sizes are defined as primary microplastics, commonly used in facial cleansers and cosmetics or as air spray media, and as carriers for certain medicines. Secondary microplastics, on the other hand, are defined as tiny fragments of plastic produced in the oceans and on land by the decomposition of larger plastic fragments. Over time, the culmination of physical, biological and chemical processes reduces the structural integrity of plastic fragments, leading to fragmentation.

The physical and chemical properties of microplastics are highly prone to change. Research has shown that under the influence of environmental factors such as runoff, tides, wind, radiation, and biological activity, microplastics not only undergo physical alterations, such as cracking and foaming but also experience chemical changes, including bond breakage and molecular fragmentation. These transformations directly impact the migration and distribution patterns of microplastic particles in aquatic environments, as well as their adsorption and desorption processes, ultimately affecting their ecological and environmental impacts (Ma, 2024). Additionally, microplastics exhibit migratory behaviour, enabling them to travel long distances under the influence of wind, runoff, and tides.

Due to the certain mobility of microplastics, they are not only prevalent in the marine environment and surface water ecosystems, but also significantly impact the subsurface environment including soil and groundwater (Geng, 2024). Studies have shown that large quantities of plastic wastes seep into the subsurface environment through different pathways, and subsequently migrate and accumulate under the action of sedimentation and surface runoff to form reservoirs in the subsurface.

Research has demonstrated that microplastics have detrimental effects on both the environment and living organisms, including humans. Toxicological studies on microplastics are generally classified into in vitro and in vivo investigations. In vitro studies are laboratory-based experiments using isolated cells or tissues to examine the toxic effects of microplastics at the cellular or tissue level. In contrast, in vivo studies involve experimentation on living organisms to assess the impact of microplastics on entire organisms or specific organs. The results of these studies have categorized the toxic effects of microplastics on human cells into several biological endpoints, including cytotoxicity, immune response, oxidative stress, barrier integrity, and genotoxicity (Osman, 2023). Four of these five endpoints were confirmed as significant biological effects of microplastics on human cells, with irregularly shaped microplastics exhibiting particularly pronounced effects. Moreover, the concentration of microplastics and the duration of exposure were found to significantly influence cytotoxic and immune responses (Danopoulos, 2022). These findings suggest that human exposure to microplastics may pose health risks. Additionally, microplastics have been shown to induce harmful alterations in the gastrointestinal physiology of marine organisms and disrupt normal metabolic processes following prolonged exposure (Qiao, 2019).

3 TREATMENT OF MICROPLASTICS

Since the initial identification of microplastics in aquatic environments in 2004, there has been an increasing focus among researchers on artificial methods for degrading microplastics. Advances in technology and equipment have led to the development of various treatment approaches, which can be broadly classified into three primary categories: physical, chemical, and biological methods. This section will provide an overview of these treatment methodologies.

3.1 Physical Method

The use of physical principles to remove microplastics is a more common filtration method. This method relies on the driving force or other external forces so that the liquid in suspension through the filtration medium, solid particles, and microplastics are retained to separate from the liquid. According to this principle, in the operation of wastewater treatment plants, often in the primary treatment of grids and sand filters, which has a simple structure, less investment and can intercept other suspended pollutants, the advantages of the wastewater suitable for microplastics concentration is high. Studies have shown that up to about 70% of microplastics can be removed by conventional sand filters (Talvitie, 2017), but in practice, only the larger particle size can be removed due to the limitations of the filter mesh, which requires the cooperation of subsequent processes.

In addition, air flotation is an effective method based on the hydrophobic separation principle. In this method, hydrophobic particles are attached to the surface of bubbles generated by foam floating, which are then brought to the gas-liquid interface. In water treatment systems, air flotation is employed to remove insoluble substances from water by introducing air under high pressure. This method offers the benefits of relatively low capital investment (due to reduced chemical costs) and high operational efficiency. Studies have shown that the removal of microplastics can reach 80% by treatment with air flotation process (Vo, 2024). However, the fact is that air flotation is not inherently suitable for analyzing plastics separation because of its poor bubble predictability, which may lead to high particle losses.

3.2 Chemical Method

Chemical methods use chemicals and chemical reactions to reduce the concentration of microplastics in the water column, and currently include advanced oxidation and photocatalysis. Advanced oxidation has an important role in pollutant removal methods, where the addition of peroxides to the system using the Fenton method enhances its ability to break down organic pollutants, and is particularly suited to the recovery of specific polymers from water. It has been shown that during exposure to Fenton treatment, large-sized microplastics gradually decompose to smaller sizes and small-sized microplastics gradually degrade (Wang, 2017). However, the drawback of this method is that once the microplastics become smaller in size, the degradation process becomes slow and often takes more than a month for the treatment to reach the standard.

It is also possible to use photocatalytic methods, which form electrons by shining light from holes into a semiconductor; later, these holes combine with H2O or OH- to produce OH- and O2. This process will affect the microplastics, causing them to break down or even mineralize into CO2 and H2O. Photolysis in natural environments occurs in the C-C backbone of the plastics. The process is divided into three steps: initiation, propagation and termination. The formed radiation particles generate peroxyl radicals throughout the process, which play an important role in the photodegradation process (Gewert, 2015). The advantage of this method is that its decomposition products are pollution-free and more environmentally friendly, but in practice the cost is higher.

3.3 Biological Method

Traditional biological methods for the treatment of pollutants often lend themselves to the natural process of helping microorganisms (mainly fungi or bacteria) to clean the environment, in which plastic materials degrade into larger plastics and microplastics due to different environmental factors. Traditionally, biodegradation occurs in four steps, (1) biodeterioration, i.e. the formation of a biofilm around the plastic polymer; (2) microorganisms undergo bio-fragmentation, producing extracellular enzymes that act on the polymer to convert it into oligomers/dimers/monomers, making it more readily available for uptake; and (3) assimilation of the oligomers/dimers/monomers occurs, where they are assembled on microorganisms and taken up by the microbial cells. (4) Mineralization occurs when metabolites such as CO2, H2O, and CH4 are produced (Sharma, 2022), thus providing energy for the degradation process. In practical studies, microbial degradation is often combined with physicochemical processes to achieve higher efficiency. The advantages of this approach are cost-effectiveness, low energy consumption, environmental friendliness, high specificity of remediation using bacteria, fewer harmful by-products, etc., but at the same time it has some disadvantages, such as the degradation process is very slow and takes a great deal of time, sometimes years, to complete.

However, some studies have also shown that there also exist emerging methods of degrading microplastics by direct action of organisms, such as the mucus obtained from a jellyfish, Aurelia-aurita, which can bind to and reduce the toxicity of nanoplastics (NPs). Its mucus can capture up to 90% of polystyrene NPs within 30 min (Geum, 2022). The treatment of the jellyfish for the removal of microplastics is done without the addition of any harmful chemicals. There is no emission problem given, which fully meets the needs of sustainable development. However, there are limitations because jellyfish only reproduce in large numbers during certain seasons, and it is not possible to capture jellyfish in their natural state in a sustainable manner.

3.4 An Example of Microplastics Treatment in a Wastewater Treatment Plant

The effluent treatment process in wastewater treatment plants (WWTPs) is typically divided into three stages. The primary treatment involves coarse and fine screening, grit and oil removal, skimming, and primary settling (sedimentation). To optimize the biochemical properties of the effluent for subsequent secondary biological treatment, most microplastics and fibrous pollutants entering the WWTP are removed through skimming and settling in the primary treatment system. Research indicates that approximately 70% to 98% of microplastics are removed during primary treatment (Iyare, 2020), with grease traps being the main removal mechanism. Microplastics are predominantly removed by adsorption onto surface solids or sludge during sedimentation.

The secondary treatment is primarily biological, targeting the removal of chemical oxygen demand (COD), biological oxygen demand (BOD), nitrogen, and phosphorus. Although not specifically designed for microplastic removal, the physical processes involved still contribute to microplastic reduction. Studies suggest that the microplastic removal rate during secondary treatment ranges from 70% to 98%. However, Talvitie et al. observed an increase in the proportion of secondary microplastics with higher levels of treatment. After activated sludge treatment, primary and secondary microplastics constituted 19% and 81% of total microplastics in the secondary effluent, respectively. Following advanced treatment, these proportions shifted to 9% and 91%, respectively. This increase in secondary microplastics may be attributed to the escape of synthetic fibers during treatment due to their small size and morphology, which allows them to pass through fine pores (Amir, 2021). Consequently, if water is discharged after the secondary treatment stage, microplastic concentrations may remain above acceptable levels, necessitating further reduction via tertiary treatment.

A variety of technologies are available for tertiary (or advanced) treatment, including Biological Aerated Filters (BAFs), sand filters, Membrane Bio-Reactors (MBRs), and ozone technology. It has been documented that primary treatment can remove about 70% to 98% of microplastics, while secondary treatment can reduce plastic concentrations in wastewater to below 20%. Tertiary treatment further decreases plastic concentrations to less than 2% (Talvitie, 2017). The effectiveness of tertiary treatment technologies, such as sand filters, sequencing batch reactors (SBRs), and media filtration processes, has been demonstrated, as tertiary-treated effluent generally contains fewer microplastic particles compared to effluent that has not undergone tertiary treatment. However, the efficiency of tertiary treatment remains a topic of debate. Research has shown that microplastic fragments, ranging from 20 to 100 micrometers, can bypass all stages of treatment, including tertiary processes, and be released into the environment through the effluent.

Thus, despite the availability of advanced treatment technologies, some microplastics will inevitably enter the environment through effluent from WWTPs, while others may enter the soil via sludge produced during primary and secondary treatment. Addressing these emissions remains a critical challenge for current microplastic degradation efforts.

4 CONCLUSION

This paper analyses in depth the classification and characteristics of microplastics and their migration and ecotoxicity in the environment, and summarizes the current main methods for microplastic treatment. It is found that although the more traditional methods can reduce the harm of microplastics to the environment to a certain extent, there are still problems such as incomplete treatment and easy to cause secondary pollution. In the emerging research methods (such as photocatalysis and the use of Aurelia-aurita jellyfish degradation method), there are more immature technology, high cost and difficult to industrialize shortcomings.

These shortcomings are particularly evident in wastewater treatment plants. The combined use of tertiary treatment has improved the removal efficiency of microplastics. However, some microplastics are still able to enter the environment through the treatment process or accumulate in the sludge. During sludge disposal, due to the lack of a targeted process and the sensitivity to climate and other factors, the impact on the concentration of microplastics is uncertain, and may be either positive or negative, resulting in doubtful compliance with the final discharge standards.

To sum up, in order to effectively deal with microplastic pollution, future research should focus on developing more efficient and environmentally friendly treatment technologies, considering the feasibility of industrialization of the technology, and at the same time, strengthening the research on the long-distance migration of microplastics in the environment and the complex pollution mechanism. At the same time, the solution to the microplastic problem not only relies on technological means, but also requires global policy support and the enhancement of public awareness in order to achieve more comprehensive environmental protection and sustainable development goals.

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